多孔介质非均质性对水油非混相驱替的影响及机理分析

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摘要 深入理解水油两相在多孔介质内的非混相驱替过程对于水驱油藏开发具有至关重要的意义. 为摸清水油两相流动模式, 本研究基于Navier-Stokes (N-S)方程模拟水油两相在微观多孔介质中的非混相驱替过程, 采用相场方法实时描述两相界面变化. 并对比了均质多孔介质模型与非均质多孔介质模型内的水驱油过程, 研究了多孔介质非均质性对于水油非混相驱替模式、驱替效率及出口端见水时间的影响. 两相流体的非混相驱替模式通常可分为三种类型: 毛管指进、稳定驱替、黏性指进. 其流动模式通常取决于两个无量纲数, 毛管数和黏度比. 本研究表明, 多孔介质非均质性会增强水油两相驱替过程界面的不稳定性, 使得非均质模型内的非混相驱替更易向黏性指进发展, 降低黏性指进产生的临界毛管数; 非均质模型的无水采收率较均质模型低, 多孔介质无水采收率并不随毛管数的增大而增大, 当驱替模式由毛管指进向黏性指进转变时, 无水采收率随毛管数的增大而减小; 相同毛管数条件下, 非均质模型出口端的见水时间比均质模型早, 黏性指进的形会减小均质与非均质模型见水时间差异. 该研究初步揭示了多孔介质非均质性对于水油非混相驱替的影响, 为深入理解油气储层中水油两相流动规律提供了理论支持.

关键词 N-S方程, 孔隙尺度, 非混相驱替, 非均质性, 采收率

1 引言

多孔介质内的非混相驱替涉及多个重要的工业及科技领域, 例如油气资源开发及提高采收率技术、地

下水污染、碳捕集与封存、非水相液体修复技术等^[1-3]. 在油气资源开发过程中, 水驱作为一种低成本与高效的开发方法得到了广泛的应用^[4]. 当水注入地层后, 水油之间存在复杂的驱替模式, 包括黏性指

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进、毛管指进以及稳定驱替^[5-8]。通常指进现象会导致大量原油束缚在多孔介质内, 从而降低原油采收率^[9,10]。因而, 在孔隙尺度研究非混相驱替模式和流动形态对于理解真实地层中的水油两相流动状态具有十分重要的作用^[11]。

大量研究人员在简单几何模型内开展了指进现象及非混相驱替的研究, 如限定宽度的单管或者Hele-Shaw模型^[12-15]。Kang等人^[16]研究了单通道中黏性手指形态与壁面润湿性、毛管数及两相黏度比之间的联系, 并给出了单一通道内形成黏性手指的临界毛管数。Redapangu等人^[17]在倾斜单管中研究了非混相驱替过程, 考虑了重力、流体黏度及密度差异对驱替过程的影响, 发现流体黏度比对于相界面前沿与尾缘移动速度的影响程度不同。Dong等人^[18]则分析了重力对单管内黏性指进现象的影响, 发现重力作用下相界面的顶端不再位于通道中心处, 并对出口端驱替液的突破时间产生了影响。这些研究从机理上解释了各因素对于非混相驱替模式的影响及指进现象形成的原因, 为多孔介质内流体非混相驱替的研究奠定了基础。然而需要指出的是, 相较于多孔介质模型, 光滑通道模型或者Hele-Shaw模型过于简单, 基于其得到的许多认识及流动规律并不适用于复杂多孔介质^[19-21]。

多孔介质内的非混相驱替研究主要基于两类多孔介质模型, 包括人为构造多孔介质模型以及天然多孔介质模型, 如岩心等^[3,11]。岩心实验或者基于真实岩心的数值模拟研究有利于研究特定地层内的流体运动规律, 但天然多孔介质模型难以独立改变其孔隙度、孔隙尺寸、配位数、均质性等物性参数^[1]。人为构造的多孔介质模型则克服了以上缺陷, 在实验及数值模拟研究中得到了广泛的应用^[22,23]。Lenormand等人^[24]通过数值模拟及实验研究了二维多孔介质中的驱替过程, 并根据毛管数和黏度比建立了区分三种驱替模式(黏性指进、毛管指进及稳定驱替)的相图。Liu等人^[25-27]利用格子玻尔兹曼方法研究了CO₂与水之间的非混相驱替, 分析两相黏度比、壁面润湿性、Bond数、毛管数及孔隙空间非均质性等因素对驱替模式的影响。Mahabadi等人^[28]研究了多孔介质孔隙半径分布、连通性等孔隙特征对于非混相驱替模式的影响, 并探究了毛管指进与黏性指进的过渡阶段对于驱替效率的影响。Ma等人^[29]基于微流控技术构建了具有高渗-低渗两个区域的非均质模型, 对比研究了CO₂气体

及CO₂泡沫在非均质模型内的驱替波及效率。Meng等人^[30]利用微通道模型模拟碳酸盐岩储层中的水驱油过程, 发现其孔隙结构差异对于注入水突破时间及剩余油分布具有重要影响。Trevisan等人^[31]在渗透率非均质性不同的人造砂岩中研究驱替及渗吸过程中非润湿流体的流动特征及捕集机制, 结果表明, 渗透率非均质性会对毛管力主导下的驱替过程产生重要影响。此外, 大量宏观尺度的研究表明, 地层非均质性是多孔介质多相流动的关键影响因素^[32]。但当前研究关于多孔介质非均质性对非混相驱替的影响机制仍不清晰。本文基于Navier-Stokes方程与相场方法耦合的微观两相流模型, 在均质多孔介质模型与非均质多孔介质模型(简称为均质模型和非均质模型)内研究不同毛管数条件下的水油非混相驱替, 从本质上解释多孔介质非均质性对于非混相驱替流动形态的影响机理, 分析了非均质性对于原油无水采收率及出口端见水时间的影响, 为深入理解地层非均质性对于水油两相驱替的影响提供了理论基础。

2 数学模型及验证

2.1 数学模型

流体在多孔介质内流动的连续性方程为^[33]

$$\nabla \cdot \mathbf{u} = 0, \quad (1)$$

式中, $\mathbf{u}$ 是速度矢量, 其运动方程为^[10]

$$\rho \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right] = \nabla \cdot (-p \mathbf{I} + \mu [\nabla \mathbf{u} + (\nabla \mathbf{u})^T]) + \mathbf{F}_{st}, \quad (2)$$

式中, p 是压力, ρ 是密度, μ 动力黏度, $\mathbf{I}$ 是单位向量; t 为时间, $\mathbf{F}_{st}$ 是界面张力项。

本研究采用Navier-Stokes方程与相场方法耦合的微观两相流模型模拟多孔介质内的非混相驱替, 利用相场变量 ϕ 区分各流体及两相界面区域。两相界面的形变与发展采用Cahn-Hilliard方程描述^[34,35]:

$$\begin{cases} \frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \left(\frac{\gamma \lambda}{\varepsilon^2} \nabla \psi \right), \\ \psi = -\nabla \cdot \varepsilon^2 \nabla \phi + (\phi^2 - 1) \phi, \end{cases} \quad (3)$$

式中, γ 为迁移率, 表示单位驱动力作用下界面的迁移速度; λ 为混合能量密度, 与力的量纲相同; ε 表示两相界面厚度; ψ 是一个辅助参数, 将四阶Cahn-Hilliard方

程拆分成两个二阶方程. 式(2)中的界面张力项可以表示为^[35]

$$\mathbf{F}_{\text{st}} = G \nabla \phi, \quad (4)$$

式中 G 为化学势, 可表示为^[36]

$$G = \lambda \left[-\nabla^2 \phi + \frac{\phi(\phi^2 - 1)}{\varepsilon^2} \right]. \quad (5)$$

壁面边界条件如下^[37]:

$$\begin{cases} \mathbf{u}_n = 0, \\ \mathbf{n} \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \psi = 0, \\ \mathbf{n} \cdot \varepsilon^2 \nabla \phi = \varepsilon^2 \cos(\theta) |\nabla \phi|, \end{cases} \quad (6)$$

式中, θ 表示固液接触角, $\mathbf{n}$ 表示壁面的法向单位向量.

2.2 模型验证

本研究采用COMSOL多物理场耦合软件对Navier-Stokes方程与Cahn-Hilliard方程进行耦合求解, 采用经典的平板分层两相流模型进行验证. 如图1所示, 通道中心 $y=0$, 润湿相流体在壁面附近($a < |y| < b$), 非润湿相流体在通道中央流动($0 < |y| < a$), 两相流体非混相. 采用外力驱动流动模拟, 在 x 方向施加恒定压力梯度并在两端采用周期性边界条件. 假定平板内的流动为稳定的泊肃叶流动, 则在平板间 y 方向任意截面流速分布存在以下理论解^[38,39]:

$$u_x(y) = \begin{cases} A_1 y^2 + C_1, & 0 \leq |y| \leq a, \\ A_2 y^2 + B_2 y + C_2, & a \leq |y| \leq b, \end{cases} \quad (7)$$

式中, $u_x(y)$ 是流体某一截面 x 方向的流速, 式中各系数分别为: $A_1 = -\frac{G}{2\mu_1}$, $A_2 = -\frac{G}{2\mu_2}$, $B_2 = -2A_2 a + 2MA_1 a$, $C_1 = (A_2 - A_1)a^2 - B_2(b-a) - A_2 b^2$, $C_2 = -A_2 b^2 - B_2 b$, $M = \eta_n / \eta_w$ 是两相流体的动力黏度比. 根据平板内的速度分布则可以得到两相流体的相对渗透率^[40]:

$$\begin{cases} k_{\text{rw}} = \frac{1}{2} S_w^2 (3 - S_w), \\ k_{\text{mw}} = S_{\text{nw}} \left[\frac{3}{2} M + S_{\text{nw}}^2 \left(1 - \frac{3}{2} M \right) \right]. \end{cases} \quad (8)$$

求解域大小为 $20 \mu\text{m} \times 200 \mu\text{m}$, 平板间距离为

图1 (网络版彩图) 平板非混相两相流体分层流动示意图
Figure 1 (Color online) Schematic of two-phase stratified flow between two parallel plates.

$4a=2b=200 \mu\text{m}$. 在 x 方向对两相流体施加的压力梯度为 $G=1 \times 10^6 \text{ Pa/m}$, x 方向两端为周期性边界条件, 上下壁面均采用无滑移边界. 非润湿相与润湿相的黏度比为0.2. 如图2所示, 数值解与根据泊肃叶流动所推导的解析解基本一致, 从而验证了本研究数学模型的准确性.

3 结果与分析

根据Lenormand等人^[24]以及Zhang等人^[1]提出的驱替模式相图, 忽略重力时二维多孔介质内的非混相驱替主要受两个无量纲参数的影响, 毛管数($Ca = u_n \eta_n / \sigma \cos(\theta)$)和黏度比($M = \eta_n / \eta_w$). 其中 u_n 表示非润湿流体的注入速度, m/s ; η_n 表示非润湿流体的黏度, mPa s ; η_w 表示润湿流体的黏度, mPa s ; θ 表示润湿流体与多孔介质壁面的接触角大小; σ 表示两相流体间的界面张力, N/m . 然而, Lenormand等人^[24]与Zhang等人^[1]采用的多孔介质模型不同而导致得到的驱替模式相图并不完全相同. Liu等人^[26]也发现, 多孔介质非均质性对于非混相驱替同样存在重要影响.

为深入理解非均质性对于非混相驱替过程的影响机理, 本研究采用小球堆积的方式建立了均质和非均质多孔介质模型, 研究不同毛管数条件下的水驱油过程, 如图3所示. 模型尺寸为 $2800 \mu\text{m} \times 6200 \mu\text{m}$, 其中左端为注入端, 采用恒速注入, 右端为采出端, 采用压力边界, 压力为0, 上下壁面为无滑移边界. 两相的密度分别为 $\rho_o = 890 \text{ kg/m}^3$, $\rho_w = 1000 \text{ kg/m}^3$; 黏度分别为 $\eta_o = 15 \text{ mPa s}$ 和 $\eta_w = 0.5 \text{ mPa s}$. 两相间的界面张力为

图2 (网络版彩图)二维平板内的分层流动流速分布及相对渗透率曲线

Figure 2 (Color online) The velocity distributions and relatively permeability of layered two-phase flow.

图3 (网络版彩图)二维均质多孔介质模型。(a) 均质多孔介质模型; (b) 非均质多孔介质模型

Figure 3 (Color online) Two-dimensional porous medium model. (a) Homogeneous porous medium; (b) heterogeneous porous medium.

0.04 N/m, 油与孔隙壁面接触角为 60° ^[14]。图中白色小球代表固体颗粒, 灰色部分表示多孔介质孔隙空间, 均质与非均质模型孔隙度均为0.625, 对均质多孔介质内的固体颗粒施加微小扰动(1~3 μm)。初始时刻多孔介质内饱和原油, 随后利用水驱替原油直至流体分布趋于稳定, 并对均质及非均质模型内的水油分布、两相流动模式、原油采收率及出口端见水时间进行对比分析。本研究在均质与非均质模型内模拟了六个不同毛管数下的水驱油过程, 毛管数由 $\log Ca = -3.48$ 增长至 $\log Ca = -2.63$ 。本研究通过改变注入端流动速度而改变驱替毛管数, 所有模拟方案其他参数均相同。

图4和5分别展示了不同毛管数驱替下注入水突破时均质与非均质模型内的油水分布。在低毛管数条件下, 均质及非均质模型内均表现出毛管指进特征。此时, 注入水在多孔介质内的流动速度缓慢, 黏滞力较小, 流动主要受毛管力控制。图6展示了毛管数 $\log Ca = -3.48$ 时非均质模型内的水油两相流动过程, 可以观察到注入水会完全占据前一个孔隙空间后再进入邻近的其他孔隙。这一现象与Liu等人^[26]的数值模拟结果及Lenormand等人^[24]的实验现象一致。同时, 注入水存在较多侧向流动, 并可能会向驱替的相反方向流动并进入新的孔隙, 如图6(e)和(f)所示, 这些特征均表明该流动为毛管指进。随着毛管数的增加, 多孔介质内注入水的流动通道数量开始增加, 宏观上表现为波及系数提高, 驱替前缘更加平缓, 展现出部分稳定驱替的特征。这一现象在均质模型内更为明显。随着毛管数的增加, 水油两相驱替过程并没有最终发展到稳定驱替阶段, 这与两相间存在较大的黏度差异有关^[24]。

在高毛管数条件下, 黏滞力对注入水的流动产生重要影响, 均质及非均质模型内出现黏性指进特征。图7展示了毛管数 $\log Ca = -2.63$ 时非均质模型内的两相流动状态, 与图6所示的驱替模式不同, 注入水仅占据部分孔隙空间后便进入后续的孔隙, 且注入水指进的发展方向主要为驱替方向, 而侧向发展的水流通量较少。此外, 高毛管数时, 注入水在较高黏滞力的作用下, 驱替前缘存在“黏性卡断”从而产生了“非连续”的指进现象, 图4(f)及图5(e)和(f)中均能观察到非连续注入水。然而, 在均质模型毛管数为 $\log Ca = -3.30$ 时同样观察到

图 4 (网络版彩图)不同毛管数下均质多孔介质模型出口端见水时水油分布. (a) $\log Ca = -3.48$; (b) $\log Ca = -3.30$; (c) $\log Ca = -3.08$; (d) $\log Ca = -2.93$; (e) $\log Ca = -2.78$; (f) $\log Ca = -2.63$

Figure 4 (Color online) The water and oil distributions at breakthrough for different capillary numbers in homogeneous porous media. (a) $\log Ca = -3.48$; (b) $\log Ca = -3.30$; (c) $\log Ca = -3.08$; (d) $\log Ca = -2.93$; (e) $\log Ca = -2.78$; (f) $\log Ca = -2.63$.

了卡断现象, 如图8所示, 水流通道被卡断并形成非连续的水团. 通常连续流体的卡断现象由两种机理产生: 一是黏滞力导致的卡断现象, 通常发生在黏滞力主导下的驱替过程; 二是毛管力主导作用下的界面不稳定所产生的流体“断裂”现象. 图8所示的驱替过程毛管数较小, 注入水的流动主要受毛管力控制, 其驱替前缘也表现出毛管指进特征. 因此, 这一卡断现象与“黏性卡断”并不相同, 而是毛管力作用下的流体“断裂”.

在中间毛管数阶段, 均质与非均质模型内呈现出不同的流动特征. 如毛管数为 $\log Ca = -2.93$ 时, 均质模型内主要表现出毛管指进特征(图4(d)), 且没有非连续指进现象的出现. 而非均质模型内则可以观察到非连续水流(图5(d)), 部分注入水仅驱替出孔隙内的部分原油后便进入后续孔隙空间, 存在黏性指进特征. 均质模型内的驱替过程约在毛管数 $\log Ca = -2.78$ 开始由毛管指进向黏性指进转变, 而非均质模型在毛管数为 $\log Ca = -2.93$ 时已经进入毛管指进与黏性指进共存的状态. 这一现象说明除了毛管数及两相流体黏度比, 非

均质性对于两相驱替模式同样存在重要影响. 在相同驱替条件下, 均质模型内的驱替前缘相较非均质模型更加均匀, 多孔介质的非均质性增强了驱替过程中相界面的不稳定性, 使得非混相驱替过程更易向黏性指进发展, 降低了黏性指进产生的临界毛管数.

为深入理解多孔介质非均质对于两相驱替过程的影响, 本研究对多孔介质内的流速分布及两相流体受力状态进行了分析. 图9对比了毛管数为 $\log Ca = -2.93$ 时均质模型与非均质模型 $x = 3100 \mu\text{m}$ 处的流速分布. 可以发现, 均质与非均质模型注入端的流速虽然相同(毛管数相同), 但孔隙内的速度分布存在差异. 均质模型多个孔隙内存在流体流动, 图9显示存在5个速度“高峰”, 但平均流速较为缓慢. 而非均质模型内仅有2个明显的速度“高峰”, 但流速较快. Kang等人^[16]的研究显示, 单通道内的非混相驱替随着毛管数的增加由稳定驱替逐渐向黏性指进发展. 虽然均质与非均质模型入口端的毛管数大小相同, 但非均质模型孔隙内的毛管数大于均质模型, 因而在相同驱替条件下, 两种多孔

图 5 (网络版彩图)不同毛管数下非均质多孔介质模型出口端见水时水油分布. (a) $\log Ca = -3.48$; (b) $\log Ca = -3.30$; (c) $\log Ca = -3.08$; (d) $\log Ca = -2.93$; (e) $\log Ca = -2.78$; (f) $\log Ca = -2.63$

Figure 5 (Color online) The water and oil distributions at breakthrough for different capillary numbers in heterogeneous porous media. (a) $\log Ca = -3.48$; (b) $\log Ca = -3.30$; (c) $\log Ca = -3.08$; (d) $\log Ca = -2.93$; (e) $\log Ca = -2.78$; (f) $\log Ca = -2.63$.

图 6 (网络版彩图)毛管数 $\log Ca = -3.48$ 时非均质模型内的水油流动状态. (a) 0.0588 s; (b) 0.06129 s; (c) 0.0648 s; (d) 0.0723 s; (e) 0.0792 s; (f) 0.087 s

Figure 6 The water and oil distributions in heterogeneous model ($\log Ca = -3.48$). (a) 0.0588 s; (b) 0.06129 s; (c) 0.0648 s; (d) 0.0723 s; (e) 0.0792 s; (f) 0.087 s.

介质内呈现出不同的驱替模式, 非均质模型在较低毛管数时形成了黏性指进现象.

图10采用简化的分叉喉道模型对均质及非均质模

型内的两相驱替过程进行了受力分析, 均质模型分叉喉道大小一致, 非均质模型分叉喉道尺寸存在差异. 在不考虑重力及浮力的作用下, 水油两相界面由主喉

图 7 (网络版彩图)毛管数 $\log Ca = -2.63$ 时非均质模型内的水油流动状态. (a) 0.0055 s; (b) 0.006 s; (c) 0.0065 s; (d) 0.0075 s; (e) 0.0085 s; (f) 0.01 s

Figure 7 (Color online) The water and oil distributions in heterogeneous model ($\log Ca = -2.63$). (a) 0.0055 s; (b) 0.006 s; (c) 0.0065 s; (d) 0.0075 s; (e) 0.0085 s; (f) 0.01 s.

图 8 (网络版彩图)注入水卡断过程(均质模型, $\log Ca = -3.30$). (a) 0.1152 s; (b) 0.1200 s; (c) 0.1260 s; (d) 0.1269 s

Figure 8 (Color online) Breaks of water plume during displacement process (homogeneous model, $\log Ca = -3.30$). (a) 0.1152 s; (b) 0.1200 s; (c) 0.1260 s; (d) 0.1269 s.

道进入分叉喉道主要受三个力作用: 毛管力(P_c)、黏滞力(P_μ)和驱替压力(P_d). 其中, 驱替压力为相界面前进的动力, 黏滞力为阻力, 毛管力则取决于多孔介质润湿性. 当动力与阻力的比值大于1时, 注入水才会驱替原油进入分叉喉道. 非均质模型由于孔隙大小不同, 分叉喉道内的毛管力大小不同, 使得分叉喉道内动力与阻力比值(动阻比)的差异增大. 当动阻比差异增大至一定程度时, 注入水会优先进入阻力小的喉道从而形成指进现象. 此时, 保持均质模型与非均质模型入口端相同的注入流速(相同毛管数)则会出现非均质模型孔隙内的流动速度大于均质模型的现象. 综上所述, 非均质模型由于孔喉尺寸不同, 增大了不同孔喉中的动

阻比差异, 在相同毛管数条件下降低驱替波及效率的同时增大了孔隙内注入水的流速, 从而使驱替过程更易向黏性指进发展.

水油两相驱替模式同样会对原油采收程度及出口端见水时间产生重要影响. 水驱开发油藏过程中从水驱开始至采出端见水称为无水采油期, 相对应采出端见水时刻多孔介质内的采收率称为无水采收率, 其是水驱开发油藏的重要指标. 图11展示了不同毛管数下均质与非均质模型出口端见水时的原油采收率, 可以发现, 多孔介质无水采收率并没有随着毛管数的增大而单调增大, 且在均质模型与非均质模型内呈现出不同的变化趋势, 这主要与多孔介质内两相驱替模式的

图9 (网络版彩图)毛管数 $\log Ca = -2.93$ 时均质与非均质模型 $x=3100 \mu\text{m}$ 处速度分布图

Figure 9 (Color online) Distribution of velocity across slice $x=3100 \mu\text{m}$ in different models when $\log Ca = -2.93$.

图10 (网络版彩图)水油两相界面进入分叉喉道受力分析

Figure 10 (Color online) Force analysis of water-oil flowing through pore throat.

差异有关。在均质模型内,毛管数小于 $\log Ca = -2.93$ 时,水油两相驱替为毛管指进,如图4(a)~(d)所示,此时多孔介质无水采收率随毛管数的增大而增大;而当毛管数增大至 $\log Ca = -2.78$ 时,驱替开始向黏性指进转变。此时毛管指进与黏性指进现象共存,随着毛管数的增加,驱替前缘流速增大并出现非连续水流,出口端见水时间提前,导致多孔介质的无水采收率随毛管数的增大而下降。在非均质模型内,毛管数小于 $\log Ca = -3.08$ 时,两相驱替模式为毛管指进,这一阶段无水采收率同样随毛管数的增加而增大;当毛管数增大到 $\log Ca = -2.93$ 时,水驱油开始向黏性指进转变,无水采收率下降。而随着毛管数继续增大,非均质模型内的驱替波及效率提高,无水采收率存在上下波动现象。综上

图11 (网络版彩图)不同毛管数下出口端见水时均质与非均质模型采收率

Figure 11 (Color online) Oil recovery when water breaks through at the outlet under different capillary numbers.

所述,均质模型与非均质模型的无水采收率均在毛管指进向黏性指进转变时出现了下降现象,其无水采收率随毛管数变化的拐点同样体现了均质性不同多孔介质内形成黏性指进的临界毛管数并不相同,非均质性会促进黏性指进的形成。图12对比了均质与非均质模型在不同毛管数下采出端的见水时间,其中见水时间比为均质模型见水时间与非均质模型见水时间比值。由于非均质模型孔隙内注入水流动速度较快,因而其出口端的见水时间较均质模型早。随着毛管数的增加,均质模型与非均质模型内均呈现黏性指进特征并出现非连续水流,出口端见水时间差异逐渐减小。

4 结论

本研究利用Navier-Stokes方程与相场方法耦合的微观两相流动模型模拟了均质多孔介质模型与非均质多孔介质模型内的水油非混相驱替过程,研究不同毛管数下的两相流动模式,并分析多孔介质非均质性对于驱替效率及出口端见水时间的影响,主要得出以下结论。

(1) 多孔介质非均质性会增强两相驱替过程界面的不稳定性,使得多孔介质内的非混相驱替更易向黏性指进发展,降低黏性指进产生的临界毛管数。其本质原因是非均质模型不同孔喉中的动阻比差异较大,在相同毛管数驱替时降低驱替波及效率的同时增大孔

图 12 (网络版彩图)不同毛管数下均质与非均质模型出口端见水时间. (a) 见水时间; (b) 见水时间比

Figure 12 (Color online) The water breakthrough time in homogeneous and heterogeneous models under different capillary numbers. (a) Water breakthrough time; (b) water breakthrough time ratio.

隙内注入水流速.

(2) 相同驱替条件下, 均质模型内的驱替前缘宏观上较非均质模型更加均匀, 波及系数较大, 使得均质模型的无水采收率较高. 此外, 多孔介质无水采收率并不随毛管数的增大而增大, 当驱替模式由毛管指进黏性指进转变时多孔介质无水采收率随毛管数的增大而减小.

(3) 相同毛管数下非均质模型出口端的见水时间比均质模型早, 黏性指进的形成会降低两种模型出口端见水时间的差异.

补充材料

基于直接求解N-S方程的方法模拟孔隙尺度水油非混相驱替过程, 其网格质量对其求解结果具有较大影响. 为保证求解精度, 对均质模型及非均质模型均进行了网格无关性验证. 如图S1所示, 均质模型采用网格数为62828、非均质模型采用网格数为70182时的方案时, 既可以确保求解精度, 同时保证计算效率. 均质模型与非均质模型的润湿角均为 90° , 驱替毛管数为 $\log Ca = -2.93$.

图 S1 (网络版彩图)三种不同网格数条件下含水饱和度随时间的变化. (a) 均质模型; (b) 非均质模型

Figure S1 (Color online) The oil recoveries with different elements. (a) Homogeneous model; (b) heterogeneous model.

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Influence of porous media heterogeneity on water-oil immiscible displacement and mechanism analysis

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Water is usually injected into the reservoirs during the development of oil and gas resources to improve oil recovery due to its effectiveness and economic feasibility. Predicting the remaining oil distributions, fluid flow pathways, and oil recovery require a solid understanding of the water-oil immiscible displacement process at the pore scale. Previous researchers have divided immiscible fluids displacement patterns into three types, namely capillary fingering, stable displacement, and viscous fingering. These patterns are strongly influenced by two dimensionless numbers, fluid viscosity ratio (M) and capillary number (Ca). Then, some phase diagrams based on viscosity ratio and capillary number can be established to describe the parameter region for different displacement patterns. However, several recent studies have shown that the heterogeneity of porous media has a significant effect on immiscible displacement. At the same time, heterogeneity is also a major characteristic of oil reservoirs. In this study, the Navier-Stokes (N-S) equation is employed to simulate the water-oil immiscible displacement in two micro models, one with a homogeneous porous medium and another with a heterogeneous one. The dynamic change of the two-phase interface is tracked by the phase-field method. The porous medium was initially saturated with oil as the wetting fluid and water were injected. A series of displacement experiments were performed for six different capillary numbers, ranging from $\log Ca = -3.48$ to -2.63 , with a fixed oil-water viscosity ratio of 30. The effects of capillary number and heterogeneity on the flow patterns were analyzed, and the displacement efficiency and breakthrough time of injected water were also investigated. The unstable displacement caused by capillary fingering occurred at low capillary numbers, and the viscous force gradually dominated the displacement process with the increase of injection rate. Nevertheless, the flow pattern did not change from capillary fingering to stable displacement but directly to viscous fingering. The latter was associated with the high oil-water viscosity ratio in our experiments. Under the same displacement conditions, the fluid dynamics at moderate capillary numbers for homogeneous and heterogeneous models were different. More specifically, heterogeneous porous media enhanced the displacement instability and promoted immiscible drainage to viscous fingering. The latter resulted in reducing the critical capillary number of viscous fingering. The primary reason was that the heterogeneity resulted in a decrease in the sweep efficiency and an increase in the flow rate of injected water in pore throats. In order to quantify the impact of heterogeneity on displacement efficiency, we also compared the oil recovery of different porous media when the injected water broke through at the outlet. The oil recovery generally increased with the capillary number prior to the flow pattern changing to viscous fingering. However, there was a slight drop in oil recovery when $\log Ca$ increased to -2.78 and -2.93 for homogeneous and heterogeneous models, respectively. The drop was related to the transition from capillary to viscous fingering in porous media. At the same time, the oil recovery in the homogeneous model was higher. The difference in flow patterns resulted in an early breakthrough for the heterogeneous model. And the formation of viscous fingering would reduce the difference in water breakthrough time. This study revealed the influence of porous media heterogeneity on immiscible displacement and provided the theoretical background for a fundamental understanding of the water-oil flow in oil reservoirs.

N-S equation, pore scale, immiscible displacement, heterogeneity, oil recovery

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